Circularly-Polarized Cavity-Backed Wearable Antenna in SIW Technology

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Abstract: This paper presents a circularly-polarized substrate integrated waveguide (SIW) antenna implemented in a textile substrate and operating at 2.45 GHz, in the industrial, scientific, and medical (ISM) frequency band. The antenna topology is based on a folded cavity with an annular ring as radiating element, and it permits to obtain compact size and low sensitivity to the environment, without deteriorating the radiating performance. These characteristics, together with the choice of adopting a textile substrate, make the SIW antenna suitable for the integration in wearable systems for body-centric applications. The electromagnetic performance of the proposed antenna achieved in simulations were verified through the measurement of the device in an anechoic chamber. The circularly-polarized antenna exhibits a maximum gain of 6.5 dBi, a radiation efficiency of 73% and a very high front-to-back ratio.

1. Introduction

The implementation of wireless systems for body-centric communication has become a hot research topic in the last few years [1], [2]. The use of textile materials as the substrate for microwave components and systems appears a very promising feature that guarantees great advantages in the realization of wearable systems for wireless communication. This growing interest has led to the implementation of several antenna topologies, including patch antennas [3], [4] and printed dipoles [5], [6], with the aim of increasing the antenna efficiency and reducing its size. Moreover, textile antennas using snap-on buttons were recently proposed [7].

A very promising approach for the implementation of components and antennas on textile is the substrate-integrated waveguide (SIW) technology [8]. SIW technology permits to integrate active components, passive elements and antennas in a single substrate. Moreover, these components may be implemented in a multilayer structure, thus reducing the size of the devices and the losses of the systems [8], [9]. These characteristics make SIW technology suitable for several applications: it can be applied in the design of many different systems for wireless area networks, mobile communication, short and medium range communication. In most of them, circular polarization is desired to improve the communication channel and the efficiency of the system. In fact, conformal SIW structures can be easily fabricated by adopting a standard fabrication process that maintains the typical flexibility of textile substrate. Moreover, the SIW circuits are completely shielded: this feature is essential for wearable applications since the interaction between microwave components and the human body must be as low as possible.

The realization of the first cavity-backed SIW antenna on textile [10] demonstrated the advantages of the combination of SIW technology with textile materials. Several alternative textile antenna topologies were proposed in the last few years, aiming at the reduction of the antenna footprint. They include single band [11], [12] and dual band [13], [14] half-mode or quarter-mode [15] substrate integrated waveguide textile antennas, as well as folded [16] and folded half-mode SIW cavity-backed antennas [17].

All the aforementioned textile SIW antennas exhibit linear polarization. On the other hand, the use of antennas with circular polarization for wearable applications was recently discussed in [18].

This paper presents a novel circularly-polarized cavity-backed SIW antenna realized with textile material. The antenna exploits two almost-degenerate resonant modes in the SIW cavity, which provide orthogonal linear polarizations: the proper excitation of the two modes by using a coaxial probe allows to get circularly polarized radiation. The antenna operates in the industrial, scientific, and medical (ISM) band ranging from 2.4 GHz to 2.4835 GHz. By exploiting a folded SIW cavity topology, the antenna was designed to minimize to footprint and to satisfy the characteristics required for the wearable applications.

The paper is organized as follows: Section 2 presents the materials and the fabrication process applied to construct the wearable antenna. Section 3 outlines the design procedure, describes the adopted cavity modes, and presents some parametric optimization results. Section 4 validates the circularly-polarized cavity-backed SIW antenna through measurements in the anechoic chamber.

2. Antenna Materials and Fabrication Process

Concerning the substrates adopted for the realization of textile antennas, in current literature different materials have been employed. Some examples of textile adopted include fleece, different kind of cotton, polyester, etc. The choice of the substrate is related to both mechanical and electrical properties of the material. On the one hand, given the specific application, the substrate should be flexible but not drapable, and it should guarantee stable mechanical characteristics (e.g. stable thickness). Moreover, its moisture regain should remain smaller than 3%, such that the antenna characteristics remain stable in varying relative humidity conditions. On the other hand, from the electrical point of view, the substrate should exhibit low losses and homogenous dielectric permittivity.

In this work, a closed-cell expanded-rubber with a thickness of 3.94 mm, usually adopted as a protective foam against impact, was chosen owing to its lightness and flexibility. This makes the foam suitable for wearable applications. Moreover, it is flame retardant, water-repellent and shock absorbing.

For the implementation of metal layers, a conductive copper-plated Taffeta fabric was used. This textile is flexible, breathable, and exhibits a suitably low surface resistivity at 2.45 GHz ($R_s = 0.18\ \Omega$/sq). Another option considered was the application of a screen printing process. However, this technique was discarded due to the low conductivity of the layers resulting from this process and the risk that the conductive ink is absorbed by the textile substrate.

Finally, in order to metalize the via holes, eyelets, fixed with an eyelet press, were applied. They preserve the flexibility of the SIW structure. Moreover, they can be fixed with computer numerical control (CNC) machine for mass production.

3. Antenna Design Procedure

In an earlier work, the authors presented a linearly-polarized SIW cavity-backed slot antenna completely realized with textile materials for short-range communication between rescue workers [10]. Owing to its topology, the antenna ensures good electromagnetic performance (radiation efficiency 68%) even in proximity of the human body. This is mainly due to the presence of the SIW cavity, which prevents the excitation of surface waves. Some improvements were obtained with a cavity-backed patch antenna [16], in terms of radiation performance (with the radiation efficiency increased to 74%) and size of the component (size reduction of 43%).

The further enhancement proposed in this paper is the development of a textile antenna with circular polarization, based on a folded SIW cavity. The antenna was designed to operate in the ISM band, with a return loss higher than 10 dB in terms of input matching, maximum radiation efficiency, and an axial ratio smaller than 3 dB.

The geometry of the antenna is shown in Fig. 1. It is based on a dual layer topology, with a rectangular SIW cavity folded around a metal septum (Fig. 1*a*). The shape of the cavity is defined by the external row of metal vias, which connect the top and bottom ground planes. In the top ground plane, an annular slot is responsible for the radiation. The metal septum, located between the two dielectric layers, is connected to the bottom ground plane by means of a metal via (Fig. 1*a*). The cavity is fed by a coaxial cable, whose inner conductor is connected to the metal septum, while the outer conductor is soldered to the bottom ground plane (Fig. 1*a*).

The folded SIW cavity has been designed to operate around the frequency of 2.45 GHz with two almost-degenerate resonant modes, similar to the TM_{120} and TM_{210} of the standard rectangular cavity (where TM is referred to the *z* axis). The electric modal fields of these modes are shown in Fig. 2. Namely, Fig. 2*a* shows the cross-cut view of one of the modes, which exhibits a minimum in the centre of the cavity and maximum electric field at the edges, near the radiating slot. In particular, the electric field of the mode appears in phase in the opposite sides of the radiating slot. The other resonant mode exhibits a similar field pattern, with a rotation of 90° around the *z* axis. Each of the two modes is able to generate a linearly-polarized radiated field (this operation principle, based on the use of a single mode, was adopted in previous works [16]). The concept is clarified by the field distribution on the radiating slot, shown in Fig. 2*b*. One mode generates the electric field distribution on the radiating slot corresponding to the black arrows, whereas the other mode generates the field corresponding to the grey arrow, with orthogonal polarization. The possibility to excite the two resonant modes of the cavity with the same amplitude and a phase difference of 90° allows to obtain a circularly polarized radiated field.

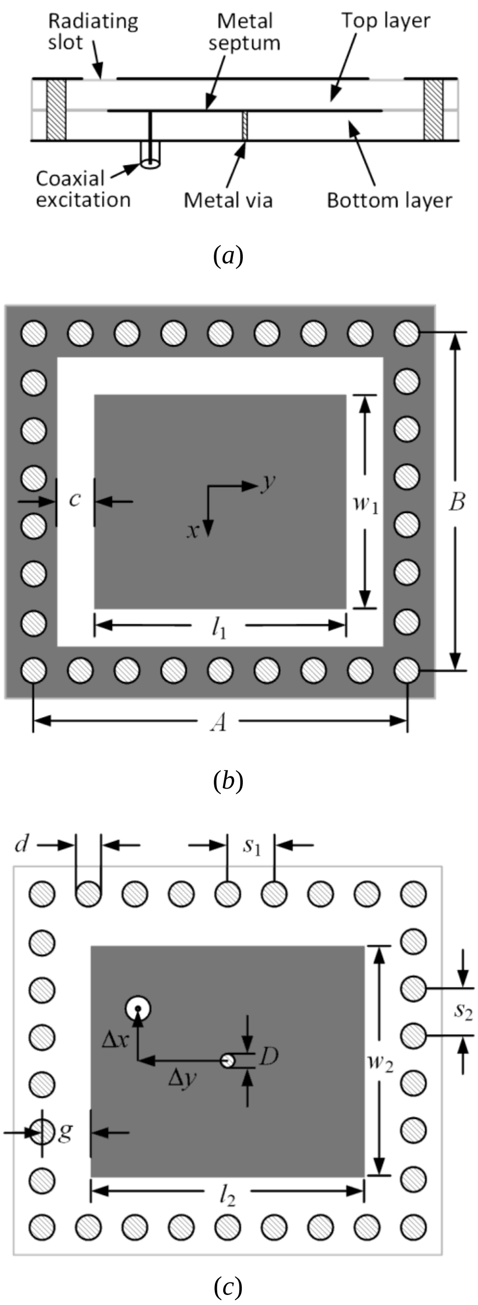
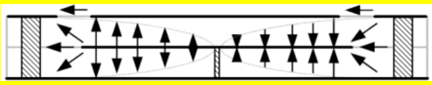


Fig. 1. *Geometry of the circular polarized SIW antenna: (a) side view; (b) top side of the top substrate layer; (c) top side of the bottom substrate layer.*



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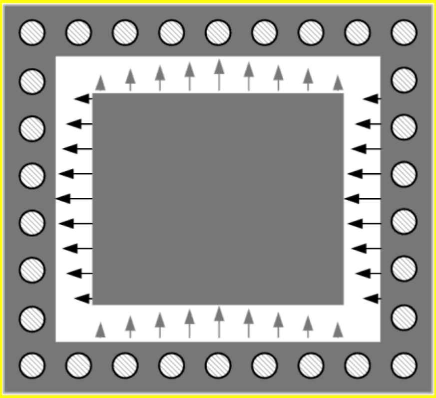


(*b*)

Fig. 2. *Electric modal field of the resonating modes: (a) cross-section view of one mode; (b) top view of the modes (black arrows: first mode, grey arrows: second mode).*

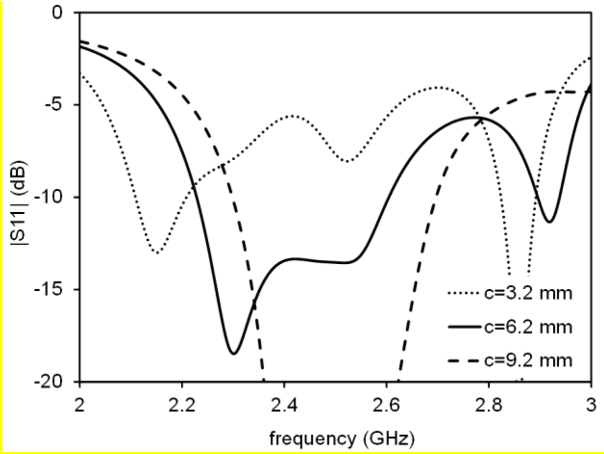
The choice of the folded rectangular SIW cavity presents some advantages. First of all, it leads to a smaller footprint of the antenna (almost 50% smaller than the classical SIW cavity), at the cost of using a double-layer manufacturing technology, with the need to process three faces. The other advantage, related to the rectangular shape, is the additional degree of freedom that allows to easily control the resonance frequencies of the two cavity modes.

The SIW antenna was designed by using the commercial electromagnetic solver Ansys HFSS. For the design of the antenna, the electrical characteristics of the textile foam determined in [16] were used ($\varepsilon_r = 1.45$, $\tan\delta = 0.017$). The optimized geometrical dimensions are reported in Tab. 1.

In the design phase, the preliminary value of the gap *g* was carefully selected: in fact, a small value of *g* increases the sensitivity to fabrication inaccuracies, thus increasing the risk of failure in the manufacturing process, while a large value reduces the compactness of the antenna.

Table 1 Dimensions of Circularly Polarized SIW Antenna

Parameter	Dimension [mm]	Parameter	Dimension [mm]
A	65.6	g	9.05
B	58.9	Δx	9.3
l_1	44.5	Δy	16.1
w_1	37.8	D	2
l_2	47.5	d	4
w_2	40.8	s_1	8.2
c	6.2	s_2	8.41



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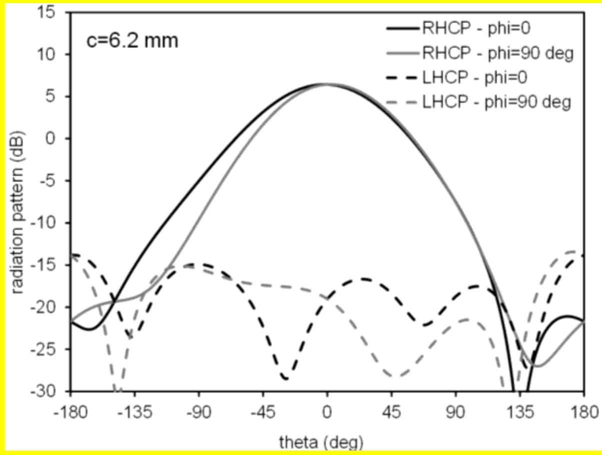

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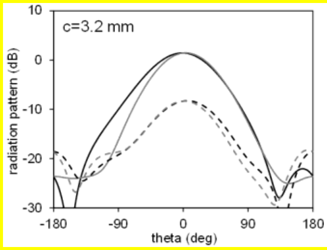

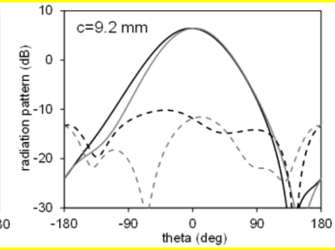

(*c*) (*d*)

Fig. 3. *Parametric study of the radiation pattern of the SIW antenna at 2.45 GHz, versus the geometrical parameter c, with all other dimensions as in Tab. 1: (a) input matching of the antenna for different values of c; (b) radiation pattern for c=6.2 mm (nominal value); (c) radiation pattern for c=3.2 mm; (d) radiation pattern for c=9.2 mm.*

Once the SIW cavity was implemented, the radiating element was designed. The antenna presents a rectangular ring cut out from the top metal layer of the folded SIW cavity (Fig. 1*b*). This configuration permits to couple the electromagnetic field of the SIW cavity with the slot in order to achieve good radiating performance. In this design step, the optimization of the dimensions of the cavity is fundamental since the completely shielded structure is affected by the presence of the ring slot. On the other hand, the size of the slot has to be optimized as well, to improve the electrical characteristics of the antenna. In particular, once the length of the ring is set to radiate optimally in the frequency

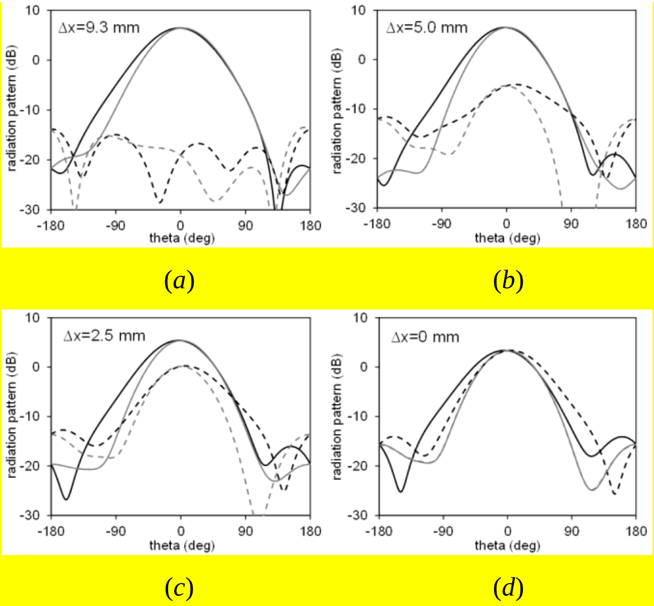

Fig. 4. *Parametric study of the radiation pattern of the SIW antenna at 2.45 GHz, versus the geometrical parameter Δx, with all other dimensions as in Tab. 1 (black solid line: RHCP at ϕ=0, grey solid line: RHCP at ϕ=90°, black dashed line: LHCP at ϕ=0, grey dashed line: LHCP at ϕ=90°): (a) Δx=9.3 mm (nominal dimension); (b) Δx=5 mm; (c) Δx=2.5 mm; (d) Δx=0 mm (symmetric structure).*

band around 2.45 GHz, a parametric analysis of the width *c* of the slot was performed, since it has a great influence on the behaviour of the SIW component (Fig. 3). Fig. 3*a* shows the input reflection coefficient of the antenna for different values of *c*, and it highlights that increasing *c* leads to a smaller bandwidth. On the other hand, Figs. 3*b*-3*d* show the radiation pattern for the same values of *c*: while the small value *c*=3.2 mm determines a poor radiation efficiency (Fig. 3*c*), larger values lead to better radiation performance, with high radiation efficiency (Figs. 3*b* and 3*d*). For these reasons, a good compromise in the choice of dimension *c* is essential.

To achieve a circular polarization, the feeding system was properly designed. In fact, the feed of the antenna has to be located in the correct position with respect to the centre of the structure (by selecting the dimensions Δ*x* and Δ*y*, Fig. 1*c*) to excite the two orthogonal modes of the SIW cavity with the same amplitude and a phase difference of 90°. Moreover, in the optimization of the position of the feed, the input matching of the SIW antenna has to be considered.

A parametric study of the position of the coaxial feed has been performed, and the radiation patterns for the RHCP and the LHCP in both principal planes at 2.45 GHz are reported in Fig. 4. In particular, the variation of dimension Δ*x* has been considered. Fig. 4*a* shows the radiation pattern for the nominal (optimal) value Δ*x*=9.3, exhibiting a mainly RHCP field and a low level of LHCP field. When the value of Δ*x* decreases, as shown in Figs. 4*b* and 4*c*, the (cross-polar) level of LHCP field increases, and in the case of Fig. 4*d* (i.e., Δ*x*=0) it reaches the level of the RHCP field. A more careful analysis of the last case shows that, when Δ*x*=0, the structure is symmetric with respect to the *yz* plane. In this case, due to symmetry, the coaxial feed excites only one resonant mode, and the radiating field is linearly polarized.

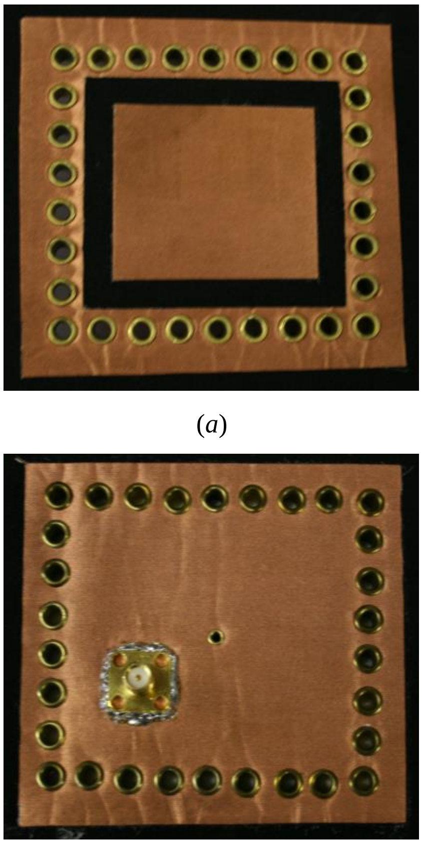

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Fig. 5. *Photograph of the prototype of the circularly polarized SIW antenna: (a) radiating side; (b) feed side.*

4. Measurement Results

The prototype of the circularly polarized cavity-backed SIW antenna was manufactured and the photographs of the front (radiating) side and of the back (feeding) side are shown in Fig. 5. The electromagnetic characteristics of the prototype were experimentally verified in order to evaluate the performance of the antenna.

First of all, the input matching of the microwave device was measured in stand-alone condition. The specification of the 2.45 GHz ISM is satisfied, as shown in Fig. 6 (return loss larger than 10 dB from 2.4 GHz to 2.4835 GHz), and a bandwidth of 337 MHz was measured. According to the simulation, the frequency response exhibits two peaks due to the almost-degenerate modes of the SIW cavity, which permit to increase the bandwidth.

Moreover, the radiation performance of the antenna was verified in an anechoic chamber. The radiation patterns of the right-hand circular polarized component (RHCP) and of the left-hand circular polarized component (LHCP) of the SIW antenna on the two principal planes (φ=0°, φ=90°) are shown in Fig. 7. The measured gain in the boresight direction is 6.5 dBi, which corresponds to a radiation efficiency of 73%. The measured front-to-back ratio is 19.4 dB.

These values validate the design of the radiating element of the antenna. The isolation with respect to objects on which the antenna is deployed is therefore complete: this feature makes the antenna particularly suitable for wearable applications.

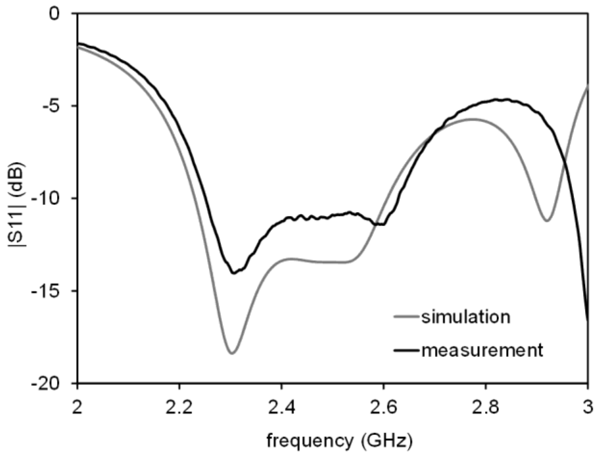


Fig. 6. *Simulated and measured input reflection coefficient of the circularly polarized SIW antenna (black lines: measurement, grey lines: simulation).*

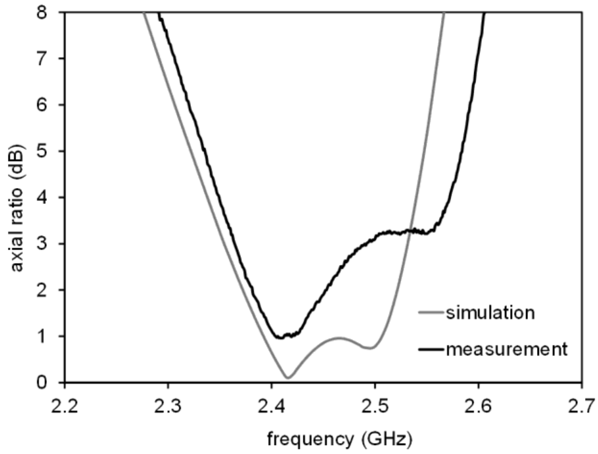
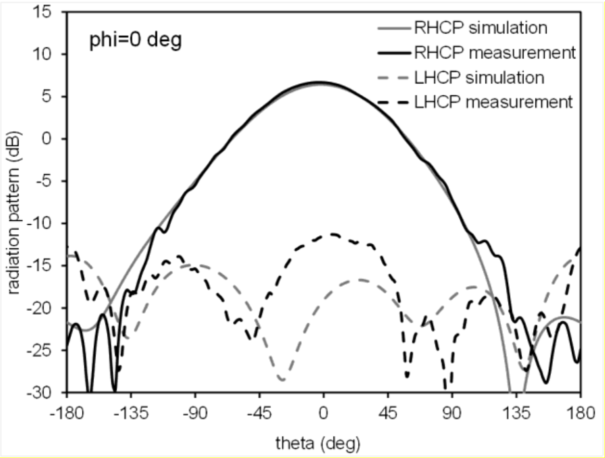


Fig. 8. *Simulated and measured axial ratio in boresight direction of the circularly polarized SIW antenna (black lines: measurement, grey lines: simulation).*



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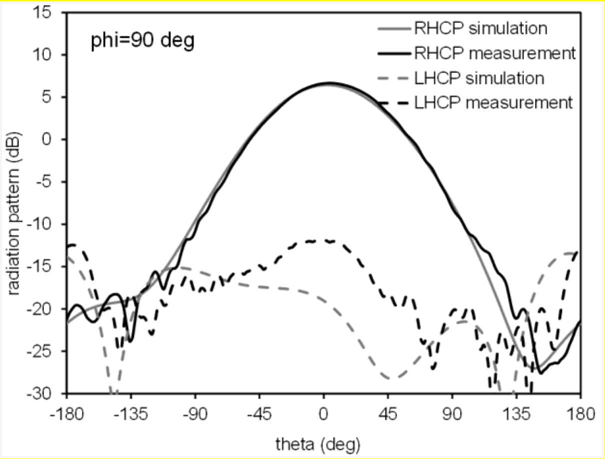

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Fig. 7. *Simulated and measured radiation pattern of the circularly polarized SIW antenna at 2.45 GHz: (a) in the plane $\phi=0°$; (b) in the plane $\phi=90°$ (black lines: measurement, grey lines: simulation, solid lines: RHCP, dashed lines: LHCP).*

Finally, the axial ratio in the boresight direction was measured (Fig. 8). Good agreement between simulated and measured results is observed. The frequency band where the axial ratio is lower than 3 dB ranges from 2.365 GHz to 2.499 GHz and therefore covers the ISM band.

5. Conclusion

A circularly-polarized folded SIW cavity-backed antenna was designed and realized onto textile substrate. The excellent performance of the antenna in terms of input matching, radiation patterns, front-to-back ratio, and axial ratio demonstrates the high efficiency that can be obtained by adopting the SIW technology onto textile substrate. The mechanical characteristics of the foam combined with the folded configuration of the antenna reduce the size and improve the comfort of the device employed in wearable systems. Furthermore, the antenna with circular polarization permits to exploit the components for specific applications, such as localization and tracking of rescue operators.

6. References

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